Evaluation of Concentrator Photovoltaic System Power Plant

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Sumitomo Electric Industries, Ltd. installed a concentrator photovoltaic (CPV) power generation system in a high solar irradiation area in Morocco and evaluated its power output performance in comparison with a crystalline silicon photovoltaic (Si-PV) system. Based on the positive result, a megawatt-class CPV power plant was built in Ouarzazate, Morocco and is now operating for demonstration purposes. The CPV system is superior to the Si-PV system in energy generation per module area and effective rated power. The performance ratio of the plant has remained almost the same throughout the year, confirming its stable operation.

Keywords: concentrator photovoltaic power generation, megawatt-class power plant, annual power generation

1. Introduction

To meet the growing demand for renewable energy-based electric power systems, the concentrator photovoltaic (CPV) power generation systems have been developed as a highly efficient power generation technology.[1]

In July 2012, Sumitomo Electric Industries, Ltd. started a demonstration test on a 100-kW CPV system at its Yokohama Works.[2] In July 2014, the CPV module passed the qualification test of the International Electrotechnical Commission (IEC) conducted by a third party certification body and was certified as the first Japanese manufacturer of CPV power generation systems.[3]

CPV systems achieve highly efficient power generation by concentrating direct solar radiation about a magnification of 100-1,000 using lenses or reflectors, and is therefore suitable for regions where the direct normal irradiance (DNI) is high (DNI $\geq$ 6 kWh/m^2/day; see Fig. 1). Under high temperature conditions, the performance of CPV systems does not decrease significantly compared to that of crystalline silicon photovoltaic (Si-PV) systems. Thus, CPV systems are expected to be put to practical use in high-temperature and high-solar-radiation regions such as the southwestern part of North America, the Republic of Chile (in South America), the Middle East, North and South Africa, Australia, the Tibet (in China), and the eastern part of Mongolia. To demonstrate the advantage of CPV systems in these regions over Si-PV systems, Sumitomo Electric conducted a field experiment in the Kingdom of Morocco, which is located in a high-temperature and high-solar-radiation region and has been actively introducing renewable energy.

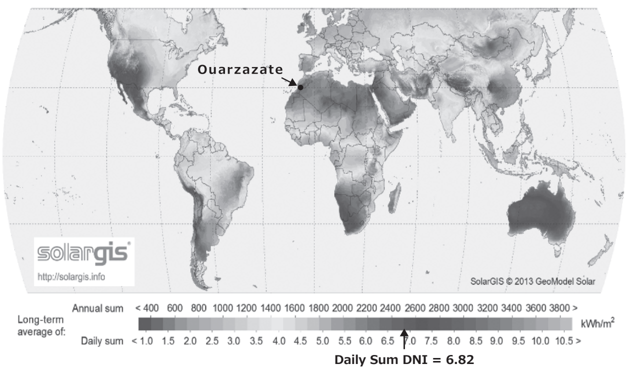

Fig. 1. Solar Resource Map of Direct Normal Irradiance (DNI)[4]

Using the CPV demonstration system and an annexed Si-PV system constructed in Ouarzazate, one of the highest solar-radiation regions in Morocco, their initial performance and power generation were compared and demonstration status was reported in 2015.[5]

This paper presents the evaluation results of annual power generation by these demonstration systems. It also reports the advantage of CPV systems based on the data obtained at a megawatt-class CPV power plant[6] constructed at an adjacent site in Ouarzazate in November 2016, and describes the efforts to improve the performance further.

2. Characteristics of CPV Systems

A CPV system is a photovoltaic power generator that concentrates the direct sunlight typically using a convex lens (similar to a magnifying glass) on small power generation elements (cells) to convert light energy into electric energy. A CPV system consists mainly of CPV modules, which comprise concentrators such as lenses, power distribution units including cells, enclosures for securing and supporting these components, and a CPV solar tracker for arranging the CPV modules on the same plane and continuously keeping these modules facing the sun.

A highly efficient multi-junction structure is used for the cells in the CPV modules by stacking epitaxial compound semiconductor layers of different energy band gaps to reduce loss in the spectral responded band. Using this structure, Soitec reported the world's highest efficiency of 46% at ×508 light concentration (508 Suns, where 1 Sun = 1 kW/m^2).[7] Meanwhile, AZUR SPACE Solar Power GmbH started mass production of cells whose mean conversion efficiency is 44%.[8] Currently, the mean conversion efficiency using these mass-produced modules is about 33-36%, which is about double that of flat Si-PV modules used at megawatt-class solar power generation plants (about 16-18%). The development of technologies, such as greater numbers of multi-junction cells, is expected to achieve ultra-high cell conversion efficiency of 50% or more in the near future. The application of these cells will improve the module conversion efficiency up to around 40%.[(9),(10)]

While CPV modules concentrate only direct sunlight on cells using lenses, Si-PV modules utilize light scattered by clouds, dust, and surrounding structures for power generation without using a lens for concentrating light. Thus, Si-PV modules can generate more power than CPV modules in such regions as Japan and Northern Europe, where direct solar radiation is weak due to cloudy and hazy weather.

Due to these characteristics, CPV's advantage increases in regions where DNI is higher than scattered light. It is essential to take into account the amount of overall power generation in the actual environment for the comparison.

3. Comparison of Annual Power Generation Between CPV and Si-PV Systems

This section reports the ratio of annual power generation between CPV and Si-PV demonstration systems[(11)] (Photo 1) that were completed in August 2015 (connected to a power grid in November 2016). The rated power of these systems obtained under the Concentrator Standard Test Conditions (CSTC)*[1] and Standard Test Conditions (STC)*[2] are 20 kW for CPV and 10 kW for Si-PV (fixed at 20°). The effective rated power*[3] of the CPV system (which can be used for fair comparison with the Si-PV standard rating) is 18.0 kW.

The generated energy per module area for effective operating days (i.e., the number of days on which both the CPV and Si-PV systems operated properly) was plotted against DNI (incidence energy for the CPV system) and GTI (incidence energy for the Si-PV system) in a graph (see Fig. 2). The total module areas of the CPV and Si-PV systems are 73.9 m^2 and 65.5 m^2, respectively. The generated energy was measured by power meters installed on the AC side.

CPV-generated energy per module area against DNI and Si-PV-generated energy against GTI showed high linearity. The seasonal variation was found to be small. The annual mean DNI and GTI, which are used to calculate the generated energy ratio, are the mean values of meteorological data during the past 20 years at the CPV demonstration site in Ouarzazate (available from Solargis).

The mean DNI and GTI during the past 20 years at the site are 6.82 kWh/m^2/day and 6.68 kWh/m^2/day, respectively. The generated energy per module area is 1.57 kWh/m^2/day for the CPV system and 0.798 kWh/m^2/day for the Si-PV system. Thus, the generated energy ratio (CPV/Si-PV) is projected to be 1.97. This result shows that at the same module area, the annual energy generation for the CPV system is 1.97 times higher than that of the Si-PV system.

Next, the energy generation per effective rated power for the effective operating days of the systems was plotted against DNI for the CPV system and GTI for the Si-PV system in a graph (see Fig. 3).

As shown in Fig. 3, generated energy per effective rated power is 6.45 kWh/kW/day for the CPV system and 5.22 kWh/kW/day for the Si-PV system. Thus, the generated energy ratio (CPV/Si-PV) is projected to be 1.23. That is, when the module rated capacity is established under the

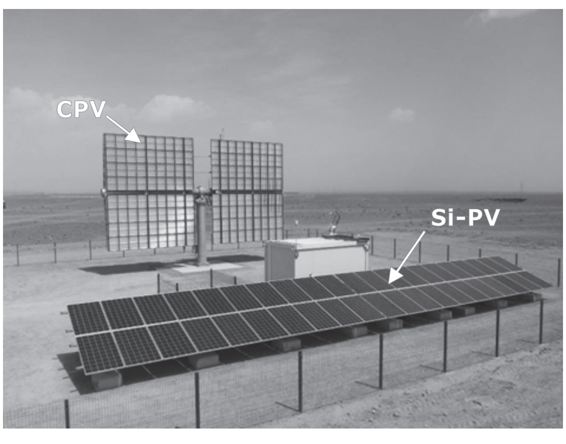

Photo 1. CPV and Si-PV Demonstration System in Ouarzazate

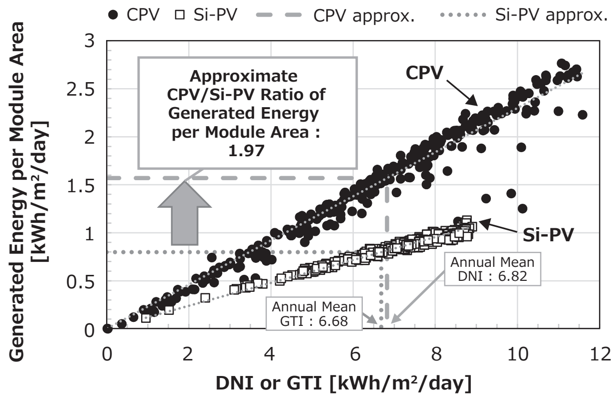

Fig. 2. Energy Generation Comparison per Module Area in Ouarzazate

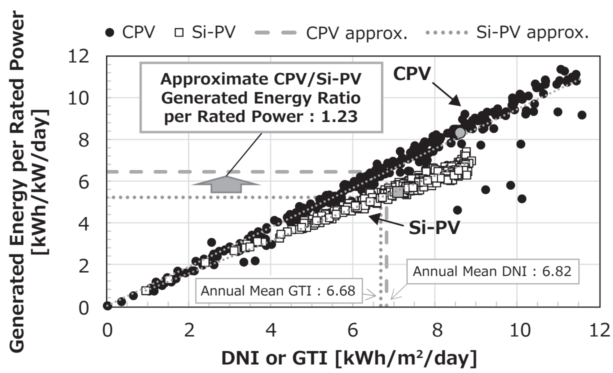

Fig. 3. Comparison of Energy Generation per Effective Rated Power in Ouarzazate

same conditions (e.g., 1 MW), the annual energy generation of the CPV system is 1.23 times higher than that of the Si-PV system (e.g., equivalent to 1.23 MW), if the systems maintain normal operation.

It should be noted that the generated energy ratio is peculiar to the meteorological environment in Ouarzazate, Morocco and is subject to change depending on the installed location.

4. Overview of the Megawatt-Class CPV Power Plant

Based on the positive results above, a megawatt-class CPV power plant was established in an adjacent area of the demonstration site in 2016. This section presents an overview of the plant (see Photo 2). The system is equipped with modules equivalent to 915 kW based on the CSTC standard rated power and 823 kW based on the effective rated power. Thirty three solar trackers are provided. The CSTC standard rated power per solar tracker is 27.7 kW, and the effective rated power is 24.9 kW.

Photo 2. Megawatt-Class CPV System Overview in Ouarzazate

The site area is 2.71 ha (156 m in the north-south direction and 174 m in the east-west direction). The solar trackers were arranged (pitch: 22 m in the north-south direction, 38 m in the east-west direction) to keep the annual power generation loss attributed to shading on CPV modules by other tracker modules to about 1.5% (Fig. 4).

For the installation of this system, Sumitomo Electric developed a solar tracking system (Photo 3).

The structure was improved from the demonstration equipment discussed above. The size of the solar tracker was increased to the extent that heavy industrial machines are not required (module installation area: 103 m^2, height: 11 m, width: 12 m approximately). The weight of the structural steel was reduced appropriately. Workability was also taken into account in the design phase. The main structural steel parts were procured locally to reduce the cost of materials, transport, and construction. A tracking controller was designed to be more resistant to the meteorological conditions, surrounding environment, and construction accuracy

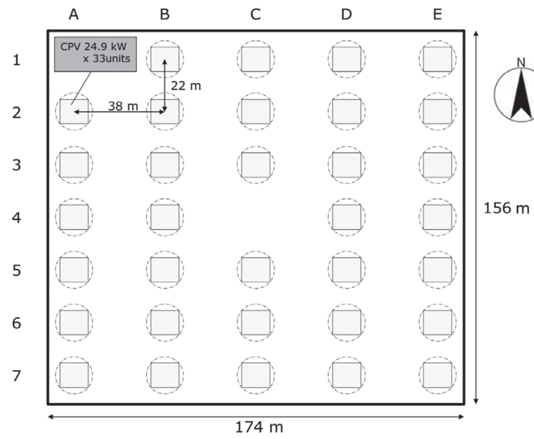

Fig. 4. CPV Power Plant Layout

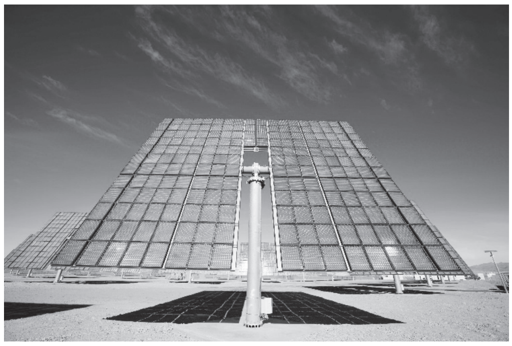

Photo 3. Developed Solar Tracking System

so that the power generation system can maximize its performance under the installation environment (Photo 4). This controller can automatically correct the direction of each solar tracker based on the power generation output. This eliminates the need to adjust individual solar trackers at megawatt-class plants where a large number of solar trackers are installed, achieving significant reduction in the adjustment and commissioning cost.

The solar trackers in this plant have a function to face CPV modules down, which is highly effective in curbing the fouling of the light-receiving lenses on the CPV

Photo 4. CPV System Tracks the Sun Precisely

modules introduced in the demonstration system discussed above (Photo 5). This function facilitated the cleaning of the light-receiving surface of the modules and increased working efficiency of the operators in a severe environment exposed to high temperatures and solar radiation.

Photo 5. Night Stow Position with the Modules Faced Down

5. Power Generation Performance

The power generation performance was verified to confirm the design validity of the CPV energy generation plant. Figures 5 and 6 present the energy generation data

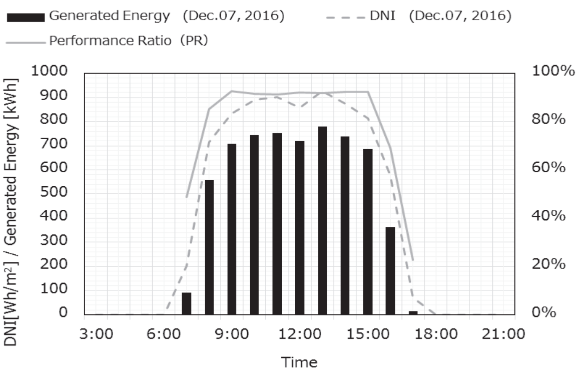

Fig. 5. Typical Energy Generation Example (immediately after commencement)

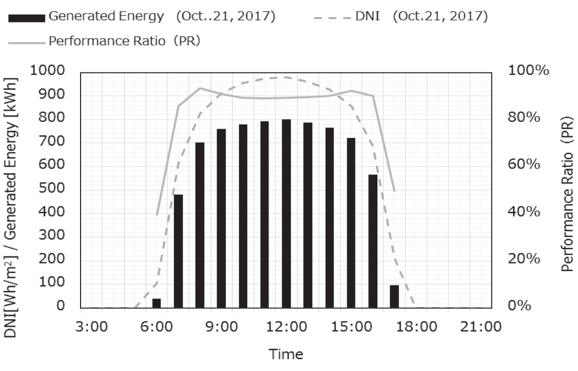

Fig. 6. Typical Energy Generation Example (After 11 months operation)

samples (immediately after commencement and of recent operation).

In general, the performance ratio (PR) is used in evaluating the performance of photovoltaic power generation systems. The PR is a value that indicates the actual power generation compared to the nominal maximum output (rated power) of a photovoltaic power generation system. The index enables impartial comparison of photovoltaic power generation systems whose installation conditions are different.

The PR of a CPV system can be calculated based on the following equation.

$$PR = (G/P) \,/\, (DNI_{in}/dni_{std})$$

G: Generated Energy [kWh]
P: System Rated Power [kW]
DNI_{in}: Direct Normal Irradiance [kWh/m^2] (incidence energy)
dni_{std}: Standard Solar Irradiation Intensity [kW/m^2]

The PR value indicates the loss subtracted from the maximum power generation capacity of installed modules (DC output). The loss generated in the process from power generation (DC output) to actual grid connection (AC output) is attributed mainly to the performance differences in modules connected in series, shading by other modules, DC-AC inverter efficiency, conductor resistance of power cable, fouling on the light-receiving surface, temperature dependence, spectral dependence, and step-up transformer. For Si-PV systems, a value of about 80-85% is used in general as a typical value.

Regarding the effective rated power of the CPV system measured on December 7, 2016 (immediately after commencement of the operation), the peak PR value was 92.7% and the daily mean PR value was 87.8%. On October 21, 2017 (11 months after commencement of the operation), the peak PR value was 93.2% and the daily mean PR value was 88.5%.

The results showed that the power generation performance remained almost unchanged during the operation period of 11 months and that the performance is equivalent to or even higher than that of the Si-PV system.

The changes in the power generation per effective

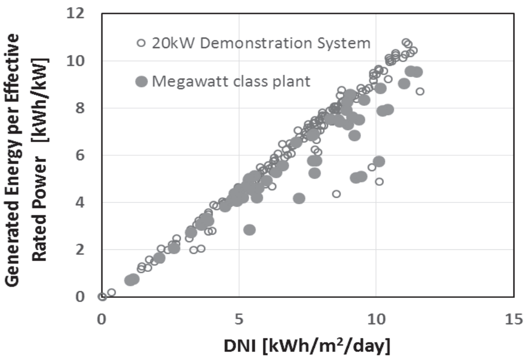

Fig. 7. Generated Energy Comparison per Effective Rated Power between 20-kW Demonstration System and Megawatt-Class Plant

rated power for the effective operating days of the 20-kW demonstration system and megawatt-class plant are also analyzed (Fig. 7).

The graph indicates that the power generation amount is almost equivalent to the power generation capacity of the installed modules, as expected, despite additional factors that can cause power generation loss such as shading by adjacent systems, extended power cables (voltage drop), and increased evacuation frequency for safety reasons under strong winds.

6. Layout of the Megawatt-Class CPV Power Generation Plant

Since there were few restrictions on land use for the power plant, the solar trackers were installed with large intervals in the plant to reduce the power generation loss caused by shadow in the morning and evening to 1.5%. In actual plant construction projects, the annual power generation per unit land area (i.e., the number of solar trackers installable per demarcated land area and generated power) is another important factor.

Because of this, the number of solar trackers installable in a limited land area for Sumitomo Electric's CPV system was also reviewed.

The installable capacity (rated power) was fixed at 823 kW (same as the capacity of this CPV power generation plant). Table 1 shows the comparison between a typical Si-PV system and this plant with CPV solar trackers installed in the densest pattern to the extent where operational interference did not occur.

Table 1. CPV Plant Land Occupation

	Typical Si-PV	This Plant	Close-packed Case
Land Occupation [ha]	1.21	2.71	0.90
Shading Loss of System Generated Energy [%]	4	1.5	11.5

The results showed that the area required for the megawatt-class CPV power plant can be reduced to about one third of the current plant at the maximum, which is smaller than that of a typical Si-PV plant. The reduced intervals increase the loss caused by shadow from adjacent CPV systems to 11.5%, but annual power generation can be maintained by increasing the number of solar trackers to be installed to compensate for the loss (10%).

It is also verified that the close-packed layout increases the power generation per unit land area to about 1.5 times greater than the typical Si-PV value.

7. Conclusion

The annual power generation performance of a 20 kW CPV demonstration system installed in Ouarzazate, Morocco was evaluated, which offered an advantage in high solar radiation regions. It was verified that the generated energy per module area and per effective rated power are about 1.97 times and 1.23 times greater, respectively, than those of the adjacent Si-PV system.

A megawatt-class CPV power plant was established on an adjacent site and its performance is under evaluation. It was verified that expected energy generation can be achieved even if the scale of the power generation system is expanded to a megawatt-class plant. The energy generation by a CPV plant was found to be equivalent to or higher than that of a typical Si-PV plant per required plant area.

Sumitomo Electric will endeavor to maximize the system availability and PR value and clarify the effectiveness of the CPV megawatt-class power generation plant to introduce even larger-scale power generation plants.

8. Acknowledgements

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Technical Terms

*1 Concentrator Standard Test Conditions (CSTC): The standard condition to measure the output of CPV modules, being defined in IEC 62670-1.
Direct nominal irradiation (DNI) = 1,000 W/m^2
Spectral irradiance = AM 1.5 D
(IEC 60904-3, ASTM G173)
Cell temperature = 25°C, wind velocity = 0 m/s

*2 Standard Test Conditions (STC): The standard condition to measure the output of crystalline silicon solar cell modules, being defined in IEC 60891 and IEC 60904.
Global nominal irradiation (GNI) = 1,000 W/m^2
Spectral irradiance = AM 1.5G
(IEC 60904-3, ASTM G173)
Cell temperature = 25°C

*3 Effective rated power: An effective nominal output value for comparing the CPV rating with the Si-PV rating. The CPV rating is determined based on the energy amount of the standard spectrum (IEC 60904-3, ASTM G173) of direct nominal irradiation (DNI) (standard incidence energy for CPV) and global nominal irradiation (GNI) (standard incidence energy for Si-PV). Specifically, the effective rated power refers to the output value when the direct nominal irradiation (DNI) (one of the concentrator standard test conditions) is 900 W/m^2.

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